CAMPAIGNS

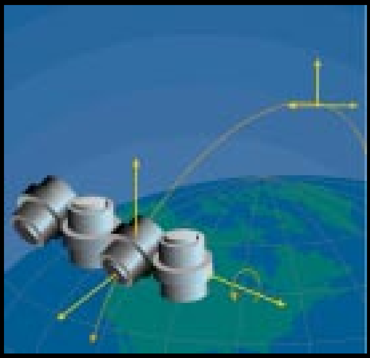
OUR THREE CAMPAIGNS ARE AREAS OF STUDY IN MICROGRAVITY THAT WILL BE APPROACHED WITH FOCUSED INVESTIGATIONS. OUR MISSIONS AND EXPERIMENTS WILL ADDRESS CAMPAIGN OBJECTIVES DURING THE PERIOD 2000–2015. AN ONGOING STRATEGIC AND PROGRAM PLANNING PROCESS WILL SELECT THE ACTUAL MISSIONS TO BE FLOWN, BASED ON SUCH FACTORS AS THE MICROGRAVITY BENEFIT AND RATIONALE, BUDGETS, TECHNOLOGY DEVELOPMENT, AND INTERNATIONAL OPPORTUNITIES.

1. *Gravitational and Relativistic Physics*
2. *Laser Cooling and Atomic Physics*
3. *Low-Temperature and Condensed-Matter Physics*

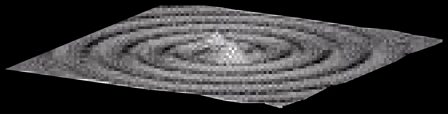
CAMPAIGN

1

Gravitational and Relativistic Physics



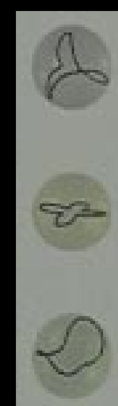
◀ *STEP will test the equivalence principle and seek to discover new long-range fields to determine whether there are other forces beyond the four currently known.*



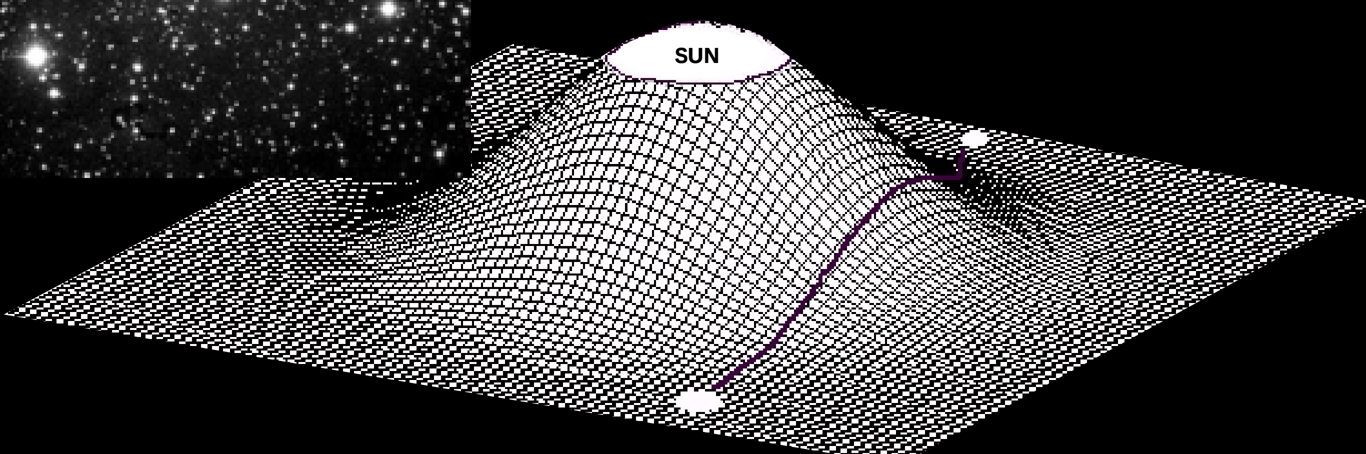
▲ *Gravity waves are predicted by current theory but have not yet been confirmed to exist. Missions are planned to detect gravitational waves from interacting white dwarf binary systems and massive black holes.*

◀ *Gravity Probe-B will verify and measure "frame-dragging" — to discover if the rotating Earth drags space–time with it.*

Can our current gravitation theories be modified to unify with quantum physics? String theory attempts to provide this unification. Each mode of vibration of the string represents a fundamental particle, and can include a graviton for the gravity forces. ▶



◀ *Gravitational dynamics missions will determine whether our current understanding of physics holds true in the strong gravity environment near black holes.*



Gravitational and Relativistic Physics

CAMPAIGN 1

OVERVIEW

Experiments in gravitational and relativistic physics test both the underlying assumptions and the consequences of Einstein's general theory of relativity, and they will discover, if present, any additional weakly coupled, long-range interactions in physical law. The tests proposed by Einstein were mainly astronomical in nature: observe the precession of the perihelion of Mercury; measure the deflection of starlight by the Sun's gravity field; measure the redshift of radio waves or light as the gravitational potential is changed. Ambitious scientists also found ways to explore aspects of the theory with controlled laboratory experiments: Pound and Rebka measured the redshift of a radio signal in a Harvard stairwell, Dicke and coworkers used an improved torsion balance apparatus to check to high precision the assumption of the equality of gravitational mass and inertial mass, and Weber used massive bars to look for gravity waves.

Access to space has opened a new frontier for testing gravitational and relativistic physics theories. Space offers several advantages to investigators testing relativity theory:

- Larger changes of gravitational potential and relative motions.
- Reduced forces on test masses or celestial bodies that cannot be modeled.
- Reduced atmospheric interference for optical or radio experiments.
- A quiet vibration environment in "drag-free" satellites.

In the following pages, we describe experiments that employ these advantages to improve tests of relativistic gravity and searches for new long-range interactions.

Key Capability Requirements

- Differential accelerometer with noise $<10^{-15}$ g over 1,000 seconds
- Charge-control system for test masses
- Gravity gradient control (helium tide)
- Drag-free satellite and micronewton thruster
- Superfluid helium dewars
- High-resolution gyroscope and rotor technology
- High-stability composite structures
- Lasers with power >1 watt and lifetime >2 years
- Laser interferometers with picometer position sensors
- Clocks with stability $>10^{-17}$
- Power source usable within 10 solar radii
- Interplanetary laser transponders

A Vital and Growing Field

Gravitational and relativistic physics (GRP) is a rapidly growing field with a long history of fundamental discovery and innovation — GRP is, in fact, at the very heart of our understanding of nature. Right now, GRP is seeing numerous exciting developments, and experimentation in space is required to provide answers to many important open questions.

Satellite Test of the Equivalence Principle (2003)

2000

Gravity Probe-B: Frame dragging and geodetic effect (2000)
Nobel Prize: Binary pulsar and GR tests (Hulse & Taylor–1993)
Nobel Prize: Electroweak theory (Glashow, Weinberg, Salam–1979)
Nobel Prize: Cosmic microwave background radiation (Penzias, Wilson–1978)
VIKING Time Delay Experiment (1976)
Gravity Probe-A: Clock redshift experiment (1976)
Binary pulsar and gravitational waves (1974–present)
Lunar laser ranging (1968–present)
Sun torsion balance (1962–1997)

Starlight bending by Sun's gravitational field (1919)
Mercury's perihelion precession anomaly resolved (1915)
Einstein: general theory of relativity (1915)
Einstein: special theory of relativity (1907)

1900

Eötvös Earth torsion balance (1892)

Laplace: lunar motion (1825)

1800

1700

Newton: pendulum experiments (1689)

1600

Galileo: "Pisa" experiments (1592)

Why Do We Study Relativistic Gravity?

Gravitational interaction not only shapes the structure of planets, stars, galaxies, and exotic objects such as neutron stars and black holes, it also guides the dynamical evolution of the universe itself. The very metrology of space and the timekeeping of our most precise atomic clocks are intimately tied to the properties of the gravitational field(s). New long-range, very weakly coupled force fields — beyond the present-day well-accepted Standard Model of particles and fields — will be best discovered from their slight modifications of the apparent gravitational interaction. Key clues for the unfinished program of unification of all physical laws could result. Space-based observations of low-frequency gravitational radiation from astrophysical sources will offer a new window into the universe and its activities.

How We Will Proceed

Mapping Einstein's World

Gravity is by far the weakest of the four known fundamental forces of nature. Yet, by virtue of its universal attraction, it is dominant at long range and governs the structure of the universe. Planets, stars, galaxies, and galaxy clusters are organized by gravity, and the expansion of the universe is under its control. As first brilliantly glimpsed by Einstein with his equivalence principle of 1907, and then more profoundly incorporated into the theory of general relativity a decade later, the very fabric of space and time has been found to be inextricably intertwined with gravity.

NASA experiments performed in space measure and probe the limits of validity of the many novel phenomena that emerge from general relativity and alternative theories of gravity. Examples of these phenomena include:

- Change of clock rates — what we call time — due to nearby gravitating matter.
- Gravitational deflection and retardation of light as it propagates near matter, which signals the non-Euclidean geometrical structure of space when viewed globally.
- Modifications of Newtonian orbits, for both planets and spacecraft, due to both the motion of the bodies and the nonlinear superposition of the gravitational fields.
- Local rotational precession, as well as acceleration of inertial space itself, because of either motion relative to matter or the motion and spinning of nearby matter.

These phenomena are very small changes to the weakest known force. To detect and measure them has invariably spurred the development and use of the most advanced and precise technologies. But once discovered and quantitatively specified here in the solar system, these modifications of gravity can then be applied to far-removed regions of the universe. The Big Bang and black holes, where relativity generates decisive "strong gravity" features, are two examples where corrections become essential to our understanding. Knowledge of gravity also has applications closer to home, such as in the Global Positioning System and laser-based orbit determinations for a variety of Earth satellites. The inclusion of general relativistic contributions to the satellite motions is essential for proper interpretation of data from satellites that are used to measure geophysical, geodesic, oceanographic, or atmospheric features of Earth.

As with all the other forces in nature, general relativity predicts that wave disturbances of its own field — gravity — are produced and propagate at the speed of light. Observations of binary pulsars have confirmed the back-action of gravitational-wave emission on its sources.

The search for low-frequency gravitational waves began with Doppler tracking of spacecraft such as Voyager and Ulysses, and will continue with Cassini. A space-based gravitational-wave observatory mission, such as LISA or OMEGA, will be designed to directly detect gravity waves predicted by theory to be generated by known binary systems. This will open a new "window into the universe," complementing the higher-frequency ground-based observatories already under construction.

Clues to the Completeness and Possible Unity of the Fundamental Forces

Several very special properties are built into Einstein's theory of general relativity. Examples are the absolute equality of inertial and gravitational mass, the universality of the gravity-induced shifts in rates of collocated clocks, and the true constancy in space and time of fundamental parameters of physical laws such as Newton's G and the electromagnetic fine-structure constant. Testing these properties requires some of the highest-precision measurements attainable in experimental physics. These measurements are best carried out in space, where experiments can exploit the low-gravity, low-noise environment of free-falling spacecraft laboratories, the great spans of experimental space and time, and the large changes in available gravity potentials and gradients.

A breakdown of general relativity's predictions will signal the existence of previously unknown long-range forces, i.e., "new physics" beyond the Standard Model of the strong, electromagnetic, and weak forces and particles. These extremely weak interactions can be spin-dependent, and can have either finite range or the traditional inverse-square nature. They will not generally be detectable in accelerator experiments.

Space-based experiments and ranging measurements of the orbits within the solar system are the best vehicles for discovering minute spatial or temporal gradients in the values of G and other assumed "constants" of nature. Even the numerical value of G, still poorly known after more than a century of ground measurements, may be better determined in space.

It is difficult to push the ground-based laboratory or lunar laser ranging tests of the universality of free-fall rates (equality of inertial and gravitational mass) more than another order of magnitude. But, through a mission like the Satellite Test of the Equivalence Principle (STEP), these tests can be extended by many orders of magnitude, down to levels where models of the unified quantum theory of matter and fields suggest violation of the equivalence principle. Even discovery of no violation would place profound constraints on the quest to develop a unified physical theory, and it would greatly enhance the range of validity for one of the most incredible invariants in nature.

Missions that place our most precise clocks in Earth orbit will improve measurements of the gravitational “redshift” of clock rates and improve long-range time-transfer techniques, which are of practical importance. They will also pave the way for missions like Spacetime, which will break fundamentally new ground in probing the effects of gravity and other possible interactions on the rates of clocks sent close to the Sun.

The apparent dynamics seen both within and between galaxies imply that the bulk of the gravitating matter of the universe is nonluminous and presently unidentified. Some candidates for this “dark matter” are associated with the existence of yet undiscovered forces. The increasingly precise measurements of solar system dynamics, and specialized mission measurements, will make more extensive and sensitive searches for these new interactions possible.

Past Space Missions

MISSION	YEAR	ACHIEVEMENT
GP-A	*1976*	*Measured Earth’s gravity-induced absolute change of clock rate to 1.4 parts in 10^4 of predicted value.*
Viking	*1976–82*	*Measured the solar gravity retardation of radio propagation between Earth and Mars landers to a part in 10^3 of its predicted value; constrained time variation of G to be less than 1 part in 10^{11} per year.*
Lunar Laser Ranging	*1969–present*	*Measured equality of Earth and Moon’s gravitational-to-inertial-mass ratios to 3 parts in 10^{13}, thereby confirming the expected strength of gravity’s nonlinearity to a few parts in 10^4; measured geodetic precession of local inertial space to half a percent of predicted value, and constrained time variation of G to be less than 3 parts in 10^{12} per year.*
LAGEOS I & II	*1992–present*	*Detected precession of the spacecraft orbit due to “dragging” of inertial space by the spinning Earth.*

Future Space Missions

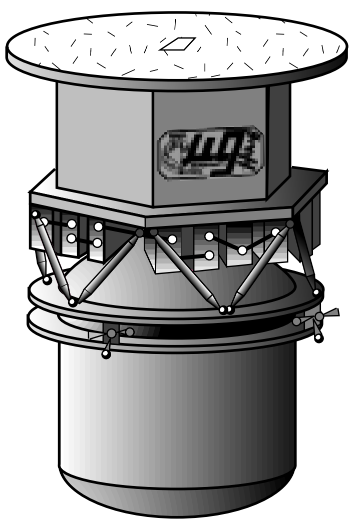
MISSION	YEAR	GOALS
GP-B	*2000*	*Will measure geodetic precession to about a part in 10^5 for an orbiting gyroscope moving through Earth's gravity, thereby improving knowledge of gravity's relativistic structure by 2 orders of magnitude; will measure to <1% the "frame dragging" of space by the gravity of Earth's rotation. (Funded by NASA Code S)*
AMS	*2002*	*Will search for and measure charged particles, including antimatter, outside Earth's atmosphere. (Jointly funded by NASA and DOE)*
Spacetime	*2003 ?*	*Will measure any differences among the shifts in rates of three distinct clocks sent close to the Sun to a precision of a part in 10^{10} of the shifts.*
STEP	*2004 ?*	*Will measure any differences in the free-fall rates of test bodies with different compositions to a part in 10^{18}, and discover new forces with corresponding precision.*
LISA	*2004 ?*	*Will detect gravitational waves from galactic binaries and massive black holes. (Funded by NASA Code S)*
SUMO	*2005*	*Will compare the rates of different types of clocks as a function of position and gravitational potential, and provide a low-phase-noise flywheel oscillator for atomic clocks.*

Example Missions

Satellite Test of the Equivalence Principle (STEP)

SCIENCE OBJECTIVES

- Test one of the most fundamental principles underlying Einstein's theory of general relativity and gravitation — the equality of inertial and gravitational mass for different bodies — to a precision of one part in 10^{18}
- Achieve 6 orders of magnitude better precision than current measurements
- Discover, or definitively rule out over an extensive range-of-strength scale, additional weakly coupled, long-range forces



The STEP satellite will be drag-free: atmospheric drag will be compensated by escaping helium gas. A simple, stable satellite provides the quiet environment needed to make these precise measurements of gravity forces.

MISSION DESCRIPTION

- Drag-free spacecraft
- LMLV-1 launch vehicle
- 400-kilometer, Sun-synchronous polar orbit
- Mission duration: 6–8 months
- Superfluid helium dewar
- Differential accelerometers

MEASUREMENT STRATEGY

- Measure relative positions of finely machined cylindrical test masses inside a superconducting low-temperature dewar

TECHNOLOGIES

- Differential accelerometer with noise $<10^{-15}$ g over 1,000 seconds
- Charge control system for test masses
- Gravity gradient control (helium tide)
- Drag-free satellite and micronewton thruster
- Superfluid helium dewar

Gravity Probe-B (GP-B) *(Code S funded)*

SCIENCE OBJECTIVES

- Verify and precisely measure two consequences of Einstein's theory of general relativity:
  - — Precession (rotation) of local inertial space from motion through Earth's gravitational field to better than a part in 10^4 (thereby improving measurement of gravity's relativistic structure by more than an order of magnitude)
  - — "Frame-dragging" precession of space produced by Earth's rotational spin

MISSION DESCRIPTION

- Four independent gyroscopes, each with a drift rate of less than 10^{-11} degree per hour
- A reference telescope sighted on a guide star
- Drag-free spacecraft
- Delta launch vehicle to 644-kilometer polar orbit
- Mission duration: 19 months
- Superfluid helium dewar

The very low temperature of Gravity Probe-B's liquid helium enables the superconducting instruments to detect the small shifts in alignment of the four quartz gyroscope spheres (one is shown above).

MEASUREMENT STRATEGIES

- Orbit four spherical quartz gyroscopes inside a liquid-helium dewar and measure their spin axes to 0.1 milliarcsecond
- Relate spin axes to guide star (IM Peg /HR 8703)
- Separately measure the geodetic and frame-drag precession effects

TECHNOLOGIES

- Superfluid helium dewar (~1.8 kelvins)
- Drag-free satellite ($<10^{-10}$ g)
- Low magnetic field ($<10^{-7}$ gauss)
- Gyro rotor technology

Superconducting Microwave Oscillator (SUMO)

SCIENCE OBJECTIVES

- Compare the rates of different types of clocks as a function of position and gravitational potential, and provide a low-phase-noise flywheel oscillator for atomic clocks
  - — Compare a microwave cavity frequency with that of an atomic clock as a function of position and gravitational potential
  - — Measure frequency differences to 1 part in 10^{17}
  - — Provide a low-phase-noise signal capable of being slaved to an atomic clock
  - — Longer term: perform a precision redshift experiment using two microwave oscillators on different vehicles

SUMO's frequency-determining element is a niobium microwave cavity. The cavity at center is coupled to a waveguide at the top and to a pump-out port at the bottom.

MISSION DESCRIPTION

- Candidate experiment for M2 mission on LTMPF on the International Space Station
- Data acquisition: three to six months

MEASUREMENT STRATEGY

- Compare microwave frequencies to the microhertz level as a function of orbital position

TECHNOLOGIES

- Ultrahigh-stability superconducting microwave oscillator
- Low-noise, phase-locked loops
- Operation at 1.2 kelvins

Gravitational Wave Missions

— Orbiting Medium Explorer for Gravitational Astrophysics (OMEGA)

— Laser Interferometer Space Antenna (LISA)

(LISA is an ESA/Code S collaboration)

SCIENCE OBJECTIVES

- Detect gravitational waves from known interacting white dwarf binary systems
- Survey close neutron star binary systems
- Observe gravitational waves from massive black holes
- Measure possible cosmic gravitational-wave background

MISSION DESCRIPTION

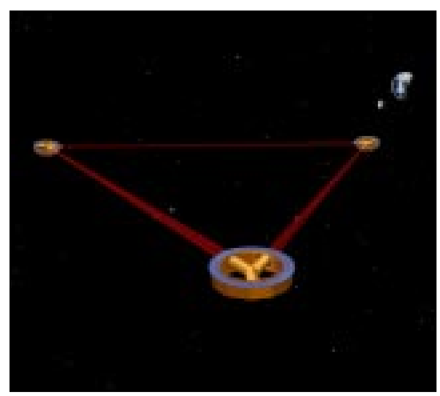
- Triangular formation of spacecraft separated by >1 million kilometers, forming a large Michelson interferometer
- Each spacecraft contains a proof mass shielded from external disturbances
- Distance between proof masses measured to 20 picometers using laser interferometry

MEASUREMENT STRATEGY

- Detect tiny changes in distance between proof masses via laser tracking to determine perturbation from gravitational waves

TECHNOLOGIES

- Accelerometers with ultralow noise
- Micronewton thrusters for drag-free control
- High-power, long-life lasers
- Heterodyne laser receivers
- High-stability composite structures
- Picometer position sensors

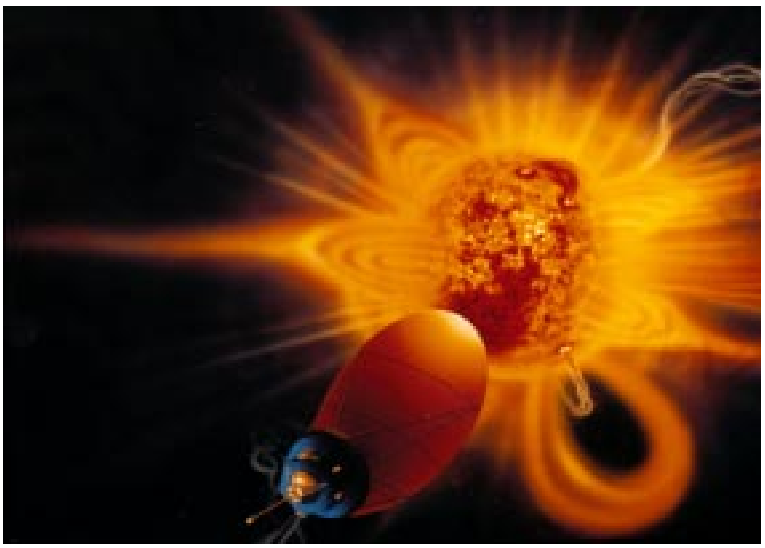


LISA's three-spacecraft configuration will use laser light beams traveling the million-kilometer distances to measure the separation of the spacecraft. The passage of a gravity wave will cause minute changes in these separations.

Spacetime Mission (STM)

SCIENCE OBJECTIVES

- Measure any differences in the gravitational frequency shifts between atomic clocks of different compositions
- Test Einstein's equivalence principle to an order of magnitude beyond existing knowledge
- Detect differential clock shifts with sensitivity 1 million times greater than GP-A measured the absolute gravitational redshift
- Directly test the hypothesis that the electromagnetic fine-structure constant varies in space–time



The Spacetime mission will send a satellite carrying two trapped-ion clocks to within 4 solar radii of the Sun. By measuring the responses of the clocks to this large gravity field, several aspects of Einstein's theory of gravity will be tested.

MISSION DESCRIPTION

- Use dual trapped-ion clock
- Use Jupiter gravity assist
- Solar flyby to within 4 radii of the Sun

MEASUREMENT STRATEGY

- Measure differences of clock rate changes in the strong gravitational potential near the Sun

TECHNOLOGIES

- Solar shield
- Power source for near-Sun use
- Low-mass structures
- Multiclocks for space experiments

Laser Interplanetary Ranging Experiment (LIRE)

SCIENCE OBJECTIVES

- Improve by at least 2 orders of magnitude the measurement precision of general relativity's relativistic structure
- Measure with at least 2 orders of magnitude better precision the time variation of the gravitational constant (G)

MISSION DESCRIPTION

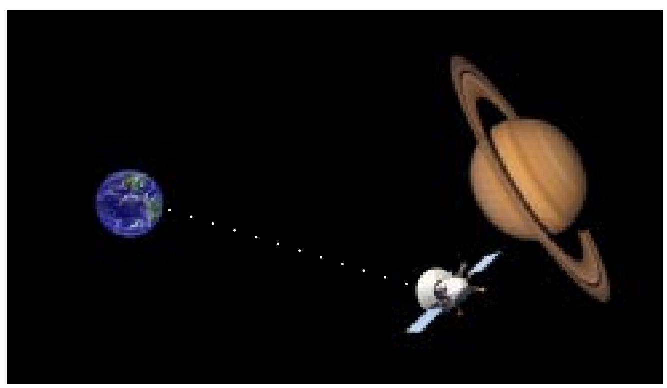
- Laser or microwave ranging to transponders located on interplanetary spacecraft or landed on or orbiting inner solar system planets or asteroids

MEASUREMENT STRATEGY

- Replace the existing "few meter" radar ranging interplanetary range measurements with "few centimeter" laser or microwave range measurements

TECHNOLOGIES

- Robust space-qualified laser or microwave transponders
- Pointing systems for guiding transponder return signals

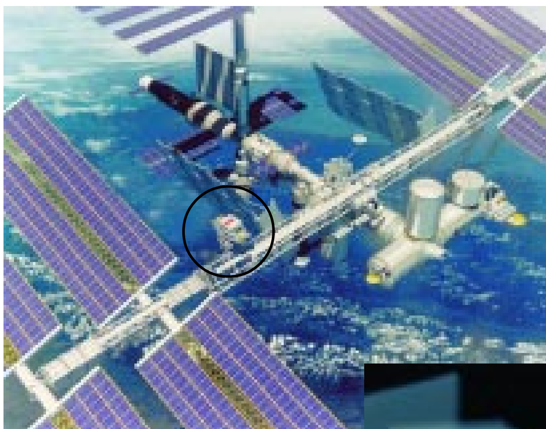


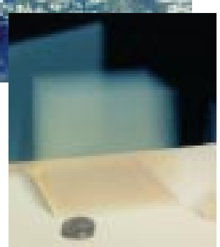
Precise laser or microwave ranging to transponders aboard interplanetary spacecraft will greatly improve knowledge of general relativity and the gravitational constant.

Alpha Magnetic Spectrometer (AMS)

SCIENCE OBJECTIVES

- Increase our understanding of the composition and origin of the universe
  - — Search for and measure charged particles, including antimatter, outside Earth's atmosphere, using the particles' measured trajectories in a magnetic field
  - — Resolution is one anti-helium nucleon per 100 million helium nuclei





The AMS (circled) aboard the International Space Station will track the paths of charged particles as they pass through the tracker planes of the detector under the influence of a magnetic field of 1500 gauss. Aerogel (inset) will be used for threshold counters.

MISSION DESCRIPTION

- The 3.5-ton instrument will be launched on the Space Shuttle and operated for 3 years as an attached payload on the International Space Station

MEASUREMENT STRATEGIES

- Time-of-flight counters detect the approach of an incoming particle
- The particle's path is determined by its charge as it traverses the magnetic field
- Silicon microstrips measure the trajectory
- Veto counters discriminate against secondary background particles
- Electronics recognize interesting events and transmit the data to scientists on Earth

TECHNOLOGIES

- Aerogel technology
- Silicon microstrip particle trackers
- Permanent magnet technology

Ground-Based Research Program

While the objective of the fundamental physics program is to perform experiments of considerable scientific significance in space, the program also supports a number of ground-based investigations. In 1998, two gravitational and relativistic experiments are under development for flight, while four investigations are in the ground-based program.

The existence of the ground-based research program permits investigations covering a wide range of topics, including theoretical studies for new experiments or concerning scheduled experiments and the interpretation of their data, and development of needed hardware and technology. Ground-based investigations are often incubators of future flight experiments.

The Satellite Energy Exchange (SEE) Project: a ground-based study concept.

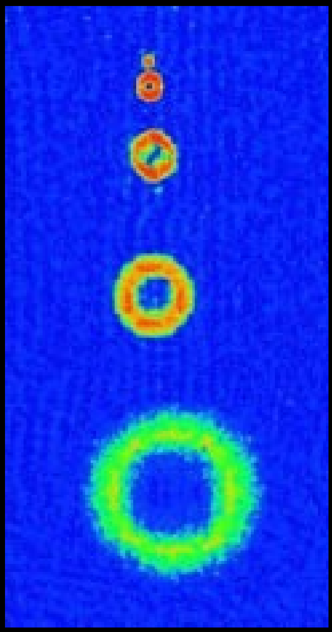
Current Ground-Based Research

INVESTIGATOR	INVESTIGATION
Prof. John A. Lipa	*Redshift Test of General Relativity on Space Station Using Superconducting Cavity Oscillators*
Prof. John A. Lipa	*Test of Supersymmetry Theory by Searching for Anomalous Short-Range Forces*
Prof. Ho Jung Paik	*Search for Spin-Mass Interaction with a Superconducting Differential Angular Accelerometer*
Dr. Alvin J. Sanders	*Research and Analysis in Support of Project Satellite Energy Exchange (SEE): Test of the Equivalence Principle and Measurement of Gravitational Interaction Parameters in an Ultraprecise Microgravity Environment*

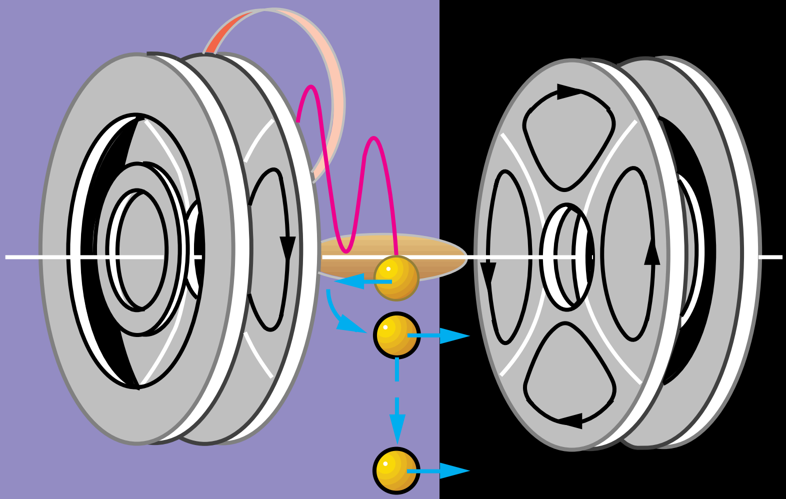
CAMPAIGN

2

Laser Cooling and Atomic Physics

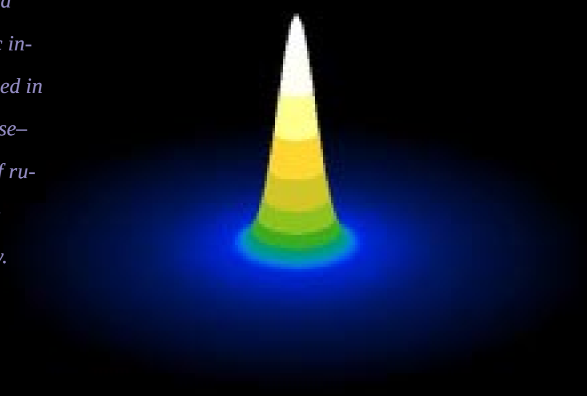


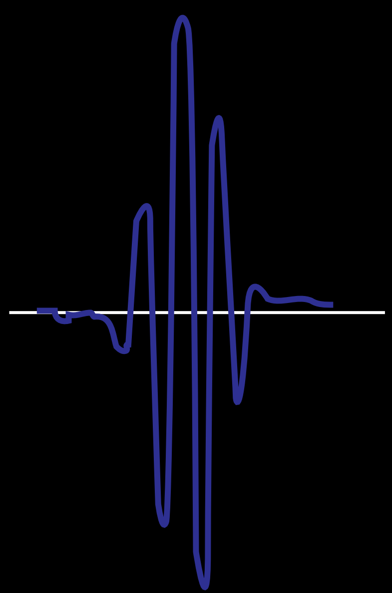
◀ An atom laser experiment will demonstrate the possibility of building improved atom lasers in microgravity.

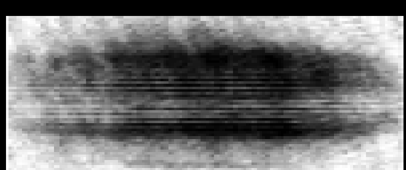


◀ We will search for the electron's electric dipole moment. Depending on its value, the Standard Model of particles and fields may have to be modified.

▶ *To find if an enhanced understanding of atomic interactions can be achieved in space, we will create Bose–Einstein condensation of rubidium and measure the temperature and density.*

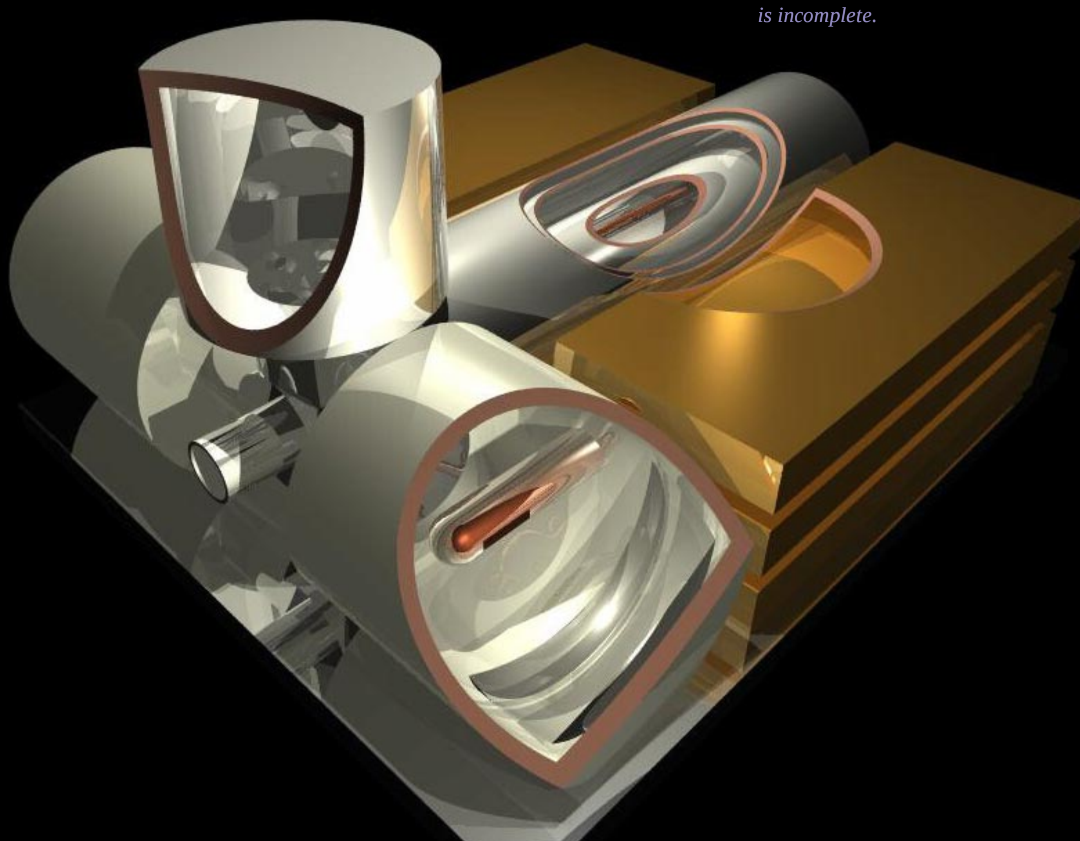






▲ *Demonstration of a matter-wave gyroscope in space will tell us if space can be used to establish stringent bounds on fundamental laws and forces of nature.*

▼ *We will use laser-cooled atomic clocks to probe the question of whether all clocks keep the same time. Perhaps our description of nature's forces is incomplete.*



Laser Cooling and Atomic Physics

CAMPAIGN 2

OVERVIEW

The purpose of this campaign is to provide answers to fundamental open questions in physics by combining the sophistication of laser cooling and atomic physics with the microgravity environment of space. Recent advances in laser cooling and manipulation of atomic motion have resulted in the demonstration of interference and entanglement of quantum states and have led to the creation of atomic clocks with superior accuracy. These techniques have enabled tests of the fundamental laws of physics with significantly greater sensitivity than ever before. Such experiments expand the range of validity of our understanding of the physical world and allow us to establish the limits at which our understanding fails.

Key Capability Requirements

- Magneto-optical trap
- Diode lasers suitable for cesium
- Diode lasers suitable for rubidium
- High-stability microwave link
- Ultrahigh vacuum technology
- Optical components
- Nonmagnetic, high-speed shutters

Novel quantum interactions, such as atomic collisions at temperatures lower than a few millionths of a kelvin, are now being studied. Recent progress has led to the dramatic observation of manifestly quantum-mechanical behavior of matter on a truly macroscopic scale.

This campaign will apply laser cooling and atomic physics in space to develop the most precise clocks, study macroscopic quantum physics, measure fundamental forces and symmetries, and explore how gravity couples to quantum systems at levels that extend far beyond those possible in Earth-bound laboratories.

The demonstration of novel quantum systems such as Bose–Einstein condensates (BECs) holds the promise of enabling new and important technologies. Experiments with laser-cooled atoms in space will allow investigations of matter in new regimes not achievable on Earth, and will support new developments and realizations of breakthrough technologies such as the atom laser — a bright source of coherent, propagating matter waves analogous to coherent propagating light waves of the optical laser — and ultraprecise atomic clocks.

A Vital and Growing Field

Atomic and optical science — laser cooling and atomic physics (LCAP) science — are rapidly growing fields with a long history of fundamental discovery and innovation. LCAP science is at the very heart of our understanding of nature and has led to many breakthrough technologies. Right now, LCAP science is seeing numerous exciting developments, and a long and prosperous future is expected.

Laser-Cooled Clock in Space (~2002)

2000

Nobel Prize: Chu, Cohen-Tannoudji, Phillips (1997)
Bose–Einstein condensation (1995)
Magneto-optical trap (1991)
Atom interferometer (1991)

Nobel Prize: Dehmelt, Paul, Ramsey (1989)
Sub-Doppler cooling (1988)

Laser Cooling of Neutrals (1982)
Nobel Prize: Bloembergen, Schawlow, Siegbahn (1981)
Trapped-ion clock (1981)

1980

Laser cooling of ions (1978)

Nobel Prize: Kastler (1966)
Nobel Prize: Townes, Basov, Prokhorov (1964)

1960

Hydrogen maser (1960)
Laser (1960)
Ion trap (1958)
Atomic clock (1954)
Maser (1954)

Nobel Prize: Rabi (1944)

1940

Rabi's molecular beam machine (1937)

1920

Why Do We Study the Physics of Atoms and Photons?

Atoms are the smallest "complex" systems that we can understand from fundamental principles, and atoms and photons are ideal systems in which to explore the quantum world. Our understanding of atomic and optical physics provides the foundation for research in astrophysics, space science, plasma physics, atmospheric science, and numerous other sciences. Additionally, atomic and optical physics provides the majority of the world's measurement standards, affecting almost every human activity from manufacturing and navigation to world trade. Since the birth of the quantum age, atomic and optical physics have provided the link between the fundamental forces and fields and the rich and complex behavior of condensed systems.

How We Will Proceed

Precise Atomic Measurements in Space

Our ability to control and manipulate nature relies on our knowledge of the fundamental constants and the precision of our measurements, and many of these measurements are best made using atoms and photons. We know that our ability to measure the properties of atoms is limited by the amount of time the atoms remain in the measurement device, and we also know that cooling atoms can help increase measurement times, which are now limited by the pull of gravity on the atoms. Fundamental experiments in atomic and optical physics need access to space. Flight opportunities are planned that will push back the frontiers of knowledge of the fundamental constants, which are the "standards" of time, space, and nature itself.

Atomic clocks with unprecedented performance will improve navigation on Earth and in space and will improve our standards of length and time, and atom interferometers will open new doors in geodesy, geology, deep space inertial navigation, and experiments in general relativity.

Exploring the Fundamental Symmetries of Nature

Hidden symmetries lie within the fundamental laws of nature. These symmetries can be broken, and the degree to which they are broken provides vital knowledge about the structure of the fundamental forces of nature. Important symmetries can be measured using atoms, but these measurements are limited by motion caused by gravity; thus, we will use cold atoms in space to search for broken symmetries at unprecedented levels and to test our current models of nature.

The search for the electric dipole moment (EDM) of the electron tests time-reversal symmetry and can be used to eliminate or support fundamental unifying models of nature such as supersymmetry. Measurement of parity nonconservation (PNC) in atoms constrains parameters such as the Weinberg angle of quantum field theories.

Macroscopic Quantum State of Atoms and Bose–Einstein Condensation

Much of our understanding of the physical world is based on microscopic quantum theory. Macroscopic quantum systems provide a unique view of the nature of the quantum world, display rich fundamental properties, and lead to important technological breakthroughs. For example, lasers could replace light bulbs, and superconductors could replace normal metals. Bose–Einstein condensation (BEC) in alkali vapors is one of the purest examples in which to study macroscopic quantum physics. However, the creation and manipulation of BEC samples is limited by gravity, and better, colder, more ideal BECs will be produced once gravity is reduced

Macroscopic quantum states of atoms could lead to atom interferometers, atom lasers that produce bright, propagating matter-wave beams, and BECs that will contribute to the technological base used by other experiments, such as precision metrology.

Harnessing the Quantum World

With the emergence of quantum theory, the possibility of new technologies based on "nonclassical" physics has captured the imagination of scientists and nonscientists alike. Recent advances in quantum physics permit new approaches to problem solving and are revising our view of computing, communication, and the very nature of information itself. At the heart of these advances is our ability to manipulate and exploit the quantum state of atoms and laser fields — we will develop the understanding and technology necessary for us to harness the quantum world.

In the future, we may build quantum computers, develop the framework for quantum information storage and processing, and investigate nearly instantaneous, secure quantum communications. We may reasonably ask whether quantum physics can be used to provide more efficient means for space travel, navigation, and communications.

Recent Discoveries and Future Possibilities

Laser-cooled and trapped atoms have been used to create the most accurate clocks ever made — accurate to 15 digits! These same clocks, when realized in microgravity, promise to show hundredfold improvement in our ability to meter time. Using laser cooling and trapping (Nobel Prize in Physics, 1997), BEC has been realized in atomic vapors. BEC allows us to investigate remarkable new quantum states of matter and the foundations of the quantum theory. Colder and purer BECs will be possible in microgravity. These BECs will be central for both basic and applied research. BECs will serve as testing grounds for macroscopic quantum physics and will improve many atomic measurements. Matter-wave interference devices have been realized, including interferometers with exquisite sensitivity to rotation and gravity. Space-based, matter-wave interferometers will set new standards in inertial and gravitational sensing for basic research, navigation, geodesy, and geology.

Example Experiments

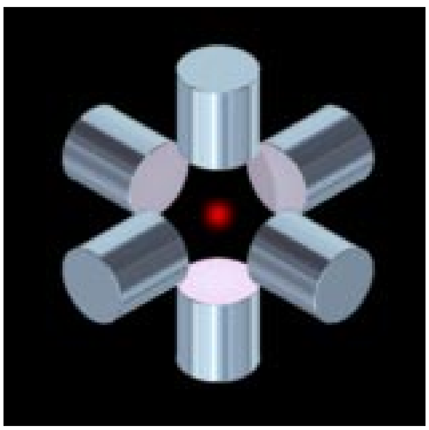
Laser-Cooled Clock Experiments (LACE)

— Primary Atomic Reference Clock in Space (PARCS)

— Rubidium Atomic Clock Experiment (RACE)

SCIENCE OBJECTIVES

- Perform measurement of cesium clock stability and improve the realization of the second — the unit of time — with 10^{-16} accuracy
- Perform measurement of the collision shift of the rubidium clock and demonstrate an accuracy of 10^{-17}
- Measure the gravitational redshift by comparing clock stability to a ground unit



The magneto-optical trap (MOT) uses laser beams impinging from the plus–minus aspects of three orthogonal directions to cool and trap alkali atoms.

MISSION DESCRIPTION

- Fly the experiment rack mounted aboard the International Space Station or as attached payload
- Utilize a multifrequency, high-stability microwave link

MEASUREMENT STRATEGIES

- Compare with the ground clock using the microwave link and high-resolution electronics
- Average over many orbits
- Transfer precision time to standard laboratories

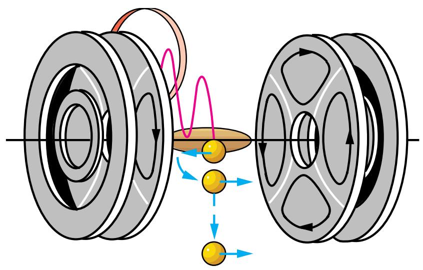
TECHNOLOGIES

- Magneto-optical trap
- Diode lasers suitable for cesium and rubidium
- High-stability optical link
- Optical component
- Nonmagnetic, high-speed shutters

Electron Dipole Moment Experiment (EDM-X)

SCIENCE OBJECTIVES

- Search for the electron electric dipole moment with laser-cooled atoms in space
- Achieve sensitivity of 10^{-30} e•cm
- Search for new physics outside the Standard Model of particles and fields



Laser-cooled cesium atoms held in a magnetic trap are subjected to a strong electric field. By probing the precession rate of these atoms, a sensitive test of the electric dipole moment can be performed.

MISSION DESCRIPTION

- Fly track mounted aboard the International Space Station or as attached payload
- Utilize a magneto-optical trap as the source of the cold atoms

MEASUREMENT STRATEGIES

- Measure spin precession frequency of ultracold cesium atoms in an electric field
- Look for a frequency shift that depends linearly on the electric field
- Use the low perturbation and long coherence time of the microgravity environment

TECHNOLOGIES

- Magneto-optical trap
- Diode lasers suitable for cesium
- Magnetic trap
- Ultrahigh vacuum
- Optical components

Bose–Einstein Condensation (BEC)

SCIENCE OBJECTIVES

- Demonstrate Bose–Einstein condensation of rubidium in space
- Perform measurements of the temperature and density and greatly extend the accessible parameter space
- Demonstrate matter-wave interference with binary mixture condensate

MISSION DESCRIPTION

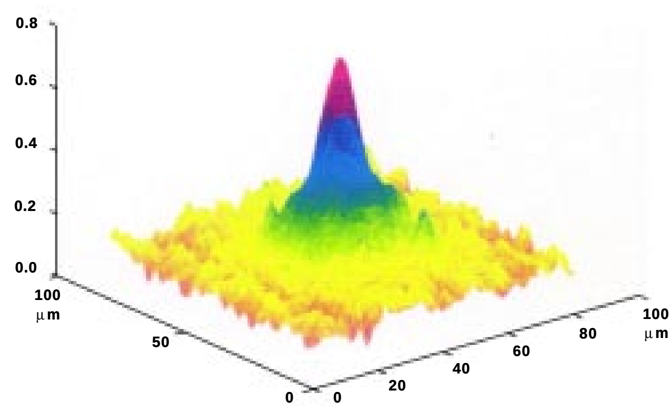
- Fly rack mounted aboard the International Space Station or as attached payload
- Utilize space magneto-optical trap
- Utilize magnetic trap for space

MEASUREMENT STRATEGIES

- Compare with the ground-based condensate
- Demonstrate lowest temperature

TECHNOLOGIES

- Magneto-optical trap
- Diode lasers suitable for rubidium
- Ultrahigh vacuum
- Magnetic trap
- Optical components



This figure shows the velocity distribution (color represents the velocity height and number of atoms at that velocity) of a cloud of sodium atoms after they have been cooled by lasers and by evaporation in a magneto-optical trap. The narrow velocity distribution demonstrates that these atoms are condensed into the Bose–Einstein condensate state.

Space Atom Laser (SAL)

SCIENCE OBJECTIVES

- Demonstrate operation of an atom laser in space
- Perform measurement of coherence properties
- Determine parameters for maximum brightness
- Demonstrate continuous operation

MISSION DESCRIPTION

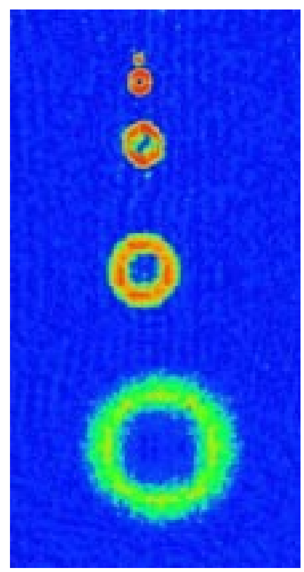
- Fly rack mounted aboard the International Space Station or as attached payload
- Utilize space magneto-optical trap
- Utilize magnetic trap for space

MEASUREMENT STRATEGIES

- Use dilute condensate
- Demonstrate continuous operation
- Explore different output couplers for the Bose–Einstein condensate

TECHNOLOGIES

- Magneto-optical trap
- Diode lasers suitable for rubidium
- Ultrahigh vacuum
- Magnetic trap
- Optical components



Four sequential pulses of matter — sodium atoms cooled to extremely low temperatures — are seen shortly after being released from a magnetic trap. These matter pulses represent the first "atom laser" in that coherent beams of matter are propagated.

Space Matter-Wave Gyroscope (SMW-G)

SCIENCE OBJECTIVES

- Demonstrate a matter-wave gyroscope using laser-cooled atoms
- Demonstrate 100-fold performance improvement over ground-based gyros
- Determine parameters for optimum performance

MISSION DESCRIPTION

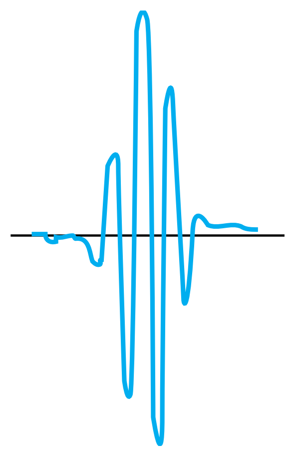
- Fly in vibration-isolated rack mount aboard the International Space Station or as attached payload
- Custom magneto-optical trap

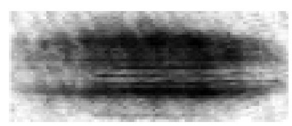
MEASUREMENT STRATEGIES

- Use Raman transitions with atomic cesium
- Compare to ground-based performance

TECHNOLOGIES

- Custom magneto-optical trap
- Diode lasers suitable for cesium





This is the interference pattern obtained by two beams of laser-cooled atoms recombined after traveling slightly different paths. The vertical axis is the number of atoms detected; the horizontal axis is the rotation rate applied to the apparatus. The coherent atom beams thus serve as a sensitive detector of rotations, or as a gyroscope.

Ground-Based Research Program

Magnets wound in a clover-leaf geometry are used in Ketterle's laboratory to contain sodium atoms against gravity while cooling them and studying BEC formation.

While the objective of the fundamental physics program is to perform experiments of considerable scientific significance in space, the program also supports a number of ground-based investigations. In 1998, two LCAP experiments are under development for flight, while 11 investigations are in the ground-based program. The existence of the ground-based research program permits investigations covering many wide-ranging topics. Included are theoretical studies of questions proposed for space experiments and questions important for the interpretation of results obtained in space. While the ground-based experiments are considered the incubator of future flight experiments, many significant results, including new discoveries, have been generated through this program.

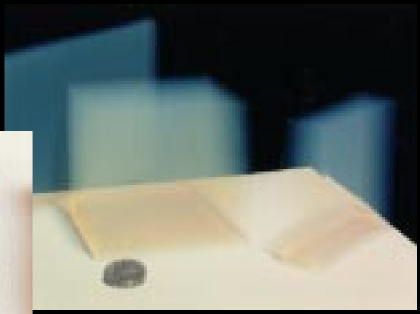
Current Ground-Based Research

INVESTIGATOR	INVESTIGATION
Prof. Kurt Gibble	*Investigation of Future Microgravity Atomic Clocks*
Dr. John L. Hall	*Fundamental Physics Using Frequency-Stabilized Lasers as Optical Atomic Clocks*
Dr. Daniel J. Heinzen	*Precision Measurements with Trapped, Laser-Cooled Atoms in a Microgravity Environment*
Dr. Tin-Lun (Jason) Ho	*Gravitational Effects in Bose–Einstein Condensate of Atomic Gases*
Prof. Randall G. Hulet	*A Quantum Degenerate Fermi Gas of Li-6 Atoms*
Prof. Randall G. Hulet	*Collisional Frequency Shifts Near Zero-Energy Resonance*
Dr. Mark A. Kasevich	*Atom Interferometry in a Microgravity Environment*
Prof. Wolfgang Ketterle	*Toward Precision Experiments with Bose–Einstein Condensates*
Prof. Warren Nagourney	*Indium Mono-Ion Oscillator II*
Dr. William D. Phillips	*Evaporative Cooling and Bose Condensates in Microgravity: Picokelvin Atoms in Space*
Dr. Ronald L. Walsworth	*Ground-Based Investigations with the Cryogenic Hydrogen Maser and the Double-Bulb Rubidium Maser*

CAMPAIGN

3

Low-Temperature and Condensed-Matter Physics



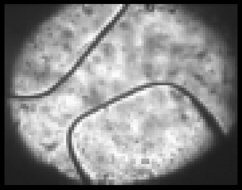
◀ *Studies of confinement and boundary effects tell us how boundaries, size, and dimensionality affect properties near a phase transition. For these studies, fluid samples can be confined between plates (left) or in a porous medium such as aerogel (above).*

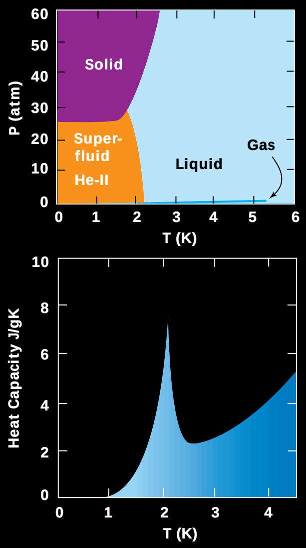
▲ *Superfluid hydrodynamics experiments will examine fluid motions and nucleation of vortices in isolated drops of superfluid helium.*

▲ *What is the nature of fractal structures and pattern formation? Studies are planned to examine how symmetry breaking is used by nature to form patterns.*

◀ *Studies of nonequilibrium phase transitions will reveal how applied forces affect the nature of a phase transition.*

▶ *Quantum solids are a future area of study: how nucleation of nonequilibrium solid phases and rapid transformation to other solid phases occurs.*





◀ *Critical phenomena experiments will help us discover whether properties near continuous phase transitions are universal, and what scaling laws exist.*

CAMPAIGN 3 Low-Temperature and Condensed-Matter Physics

OVERVIEW

The purpose of this campaign is to employ the low-gravity conditions of space to reveal the organizing principles governing many-body interactions of matter at macroscopic scales. From this understanding, we will investigate how these principles are determined by the fundamental laws governing interactions at microscopic scales of length and time. The campaign concentrates on studying ultrapure model systems possessing extraordinary properties, such as liquid helium and the superfluid–normal fluid transition in that liquid. Gravity is an obstacle to high-precision experiments in an Earth-bound laboratory. In most systems, gravity stratifies the density field and creates inhomogeneity in fluid samples. In some cases, a phenomenon simply cannot be observed on Earth. The low-gravity environment of Earth orbit provides a unique tool for the pursuit of uncovering the organizing principles governing the behavior of matter.

While many of these tests can be performed at room temperature, it is the low-temperature environment, with its uniquely low (intrinsic) thermal noise, that enables high-precision experimental tests of fundamental theories. The special combination of low gravity and low temperatures provides conditions that can greatly benefit experiments. By clarifying issues in such well-characterized testbed systems in low gravity, insights can be derived that can then be applied to predict the behavior of more complicated systems. These insights also have immediate and direct impact on understanding other systems in fields such as elementary particle physics, laser cooling and atomic physics, and gravitational and relativistic physics.

The microgravity research in low-temperature and condensed-matter physics drives technology development in two ways: by constantly demanding and developing technologies beyond the current state of the art, and by generating new research results that form the knowledge foundation for new technology development. Technology accomplishments to date include creation of the most sensitive thermometer ($<10^{-9}$ kelvin), best control of temperature, highest-sensitivity pressure transducer, a porous plug for liquid helium vent in orbit, a reusable low-temperature flight facility, and remote control of space experiments.

Key Capability Requirements

- Small high-resolution thermometers for operation near 0.9, 2.17, and 3.3 kelvins
- Picowatt thermal control
- Miniature reliable cryogenic valves
- Vibration isolation
- High-resolution pressure transducer and controller
- Low-noise thermal-wave generator and detector
- Cooler to reach 0.4 kelvin
- Optical access to the experimental cell at low temperature
- 1D and 2D confinement media
- High-speed image capture
- Drop-control technology

A Vital and Growing Field

Low-temperature and condensed-matter physics (LTCMP) is a rapidly growing field with a long history of fundamental discovery and innovation. The field is currently seeing numerous exciting developments. The accompanying timeline traces the development of gas liquefaction for practical use and depicts Nobel Prizes awarded in LTCMP.

2000

Confined Helium Experiment (1997)
Nobel Prize: Superfluid helium-3 (Osheroff, Richardson, Lee–1996)
Lambda Point Experiment (1991)
Nobel Prize: High-temperature superconductivity (Bednorz, Mueller–1987)
Nobel Prize: Quantum Hall effect (Von Klitzing, 1985)
Nobel Prize: RG theory of critical phenomena (Wilson, 1982)

Nobel Prize: Magnetic and disordered solids (Anderson, Mott, van Vleck–1977)
Nobel Prize: Tunneling (Esaki, Giaver, Josephson–1973)
Nobel Prize: Theory of superconductivity (Bardeen, Cooper, Schrieffer–1972)

Nobel Prize: Theory of liquid helium (Landau, 1962)

Nobel Prize: Bubble chamber (Glazer, 1960)
Freeze-dried foods •Liquified natural gas •Cryosurgery
Oxygen for life support

1950

Nobel Prize: Adiabatic demagnetization (1950)
First commercial liquid helium plant

German V-2 rocket uses liquid oxygen (1944)

Nobel Prize: Discovery of superconductivity (Kamerlingh-Onnes, 1913)
Nobel Prize: Fluid equation of state (van der Waals, 1910)
Helium liquified (1908)

1900

Air liquified and distilled (1894)

Dewar's vacuum vessel (1888)

Refrigerated ships (1882)

Liquid oxygen produced (1877)

1850

Why Do We Study Low-Temperature and Condensed-Matter Physics?

The physics of continuous phase transitions and of macroscopic quantum systems under ideal conditions have been explored in detail in ground-based experiments. Fundamental theories have been developed to explain the unusual behavior in these systems. For example, using precise measurements in liquid helium, investigators established in 1955–1960 that the anomaly in the specific heat remains sharp within a microdegree of the phase transition, thereby eliminating theories predicting a quasitransition possessing a rounded specific heat.

The special interest in critical phenomena follows because the theoretical explanation, renormalization group (RG) theory, has implications for many diverse fundamental and applied research areas, including weather modeling, metallurgy, oil field recovery, elementary particle physics, and cosmology. The region very close to the critical transition, where correction terms are small compared to critical anomalies, provides the best tests of RG theory. The unique properties of liquid helium — the lack of strains, impurities, imperfections, etc. — make it the best system for high-resolution tests of RG theory. The one remaining inhomogeneity that broadens the transition is the density nonuniformity caused by Earth's gravity.

Though helium is the best model system for many measurements, some important properties are not observable at the superfluid transition, so experiments at gas–liquid critical points are required to explore these aspects of the transitions. Here again, the density inhomogeneity limits the resolution of Earth-bound experiments. Eliminating this nonuniformity by performing the experiment in orbit provides unique opportunities to investigate this behavior. Additionally, all is not yet understood about this system's behavior under unusual conditions, such as nonequilibrium or confinement, close to the phase transition region.

In addition, the special interest in macroscopic quantum systems follows because superfluid helium represents a testbed possessing many desirable properties for exploring the implications of quantum theory and other theories of broad application. The superfluid transition in liquid helium will continue to provide a major testing ground for basic theoretical principles and methods in the foreseeable future.

How We Will Proceed

Studies of Critical Phase Transitions

The specific heat of ^{4}He measured by the Lambda Point Experiment in space validates the RG theory to within a billionth of a kelvin of the superfluid transition temperature, a hundredfold advance over the prior state of knowledge. The density and the superfluid density have been measured on Earth to within a millionth of a kelvin of the transition, establishing in great detail that these properties satisfy scaling behavior under a wide range of conditions. The thermal conductivity of ^{4}He has been measured also to within a millionth of a kelvin of the transition. However, existing data are inconsistent with theories close to the transition, and present boundary resistance measurements are incomplete and inconsistent with known theories.

Measurements near the tricritical point of ^{3}He–^{4}He mixtures are severely limited by the gravity-induced density nonuniformities and concentration gradients, and the approach to the transition has been limited. Tests of the universality of the critical exponents and amplitudes, characterizing the anomalous properties under many varied conditions, have been performed with resolutions at the percent level or better. Small departures from the predictions of theory are found.

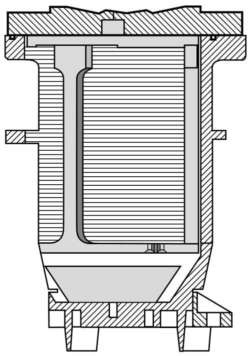
We will examine the universality of the critical exponents, a fundamental aspect of all phase transition theories, by testing the invariance of the superfluid density exponent of ^{4}He under various pressures. We will perform a stringent test of the scaling hypothesis between critical exponents, another fundamental aspect of phase transition theories, near the ^{3}He critical point. Additionally, we will conduct measurements on critical exponents near the tricritical point of ^{3}He–^{4}He mixtures, thereby providing a severe test of exact theoretical predictions.

We will improve on all these studies of critical phase transitions by performing them in the microgravity environment of space. Specifically, we will —

- Investigate universality at continuous phase transitions.
- Study properties of liquid helium confined to different geometries and sizes, using microchannel plates for cylindrical confinement and silicon plates for planar confinement.
- Investigate scaling laws at gas–liquid critical points.
- Study properties of helium mixtures near special points of the phase diagram.

Studies of Nonlinear Phenomena

Theories exist for nonlinear dynamic behaviors very near a phase transition. On Earth, gravity effects dominate when the transition temperature is approached — thus, no definitive measurements exist where the theory is best tested. The properties of the liquid in the region near the interface between the two phases can be explored in detail only in space. Existing measurements for how the phase transition temperature is affected by a heat flow disagree with the predictions of theory, and a theoretical prediction that the heat conduction will display hysteresis near the transition has not been observed on Earth.

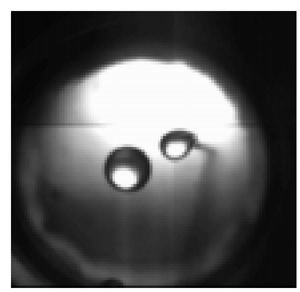


Helium confined between plates, as depicted here, demonstrates how the size and number of dimensions affect the measured properties. On Earth, gravity-induced density gradients limit the closeness of approach to a phase transition.

We will examine the nonlinear behavior of critical thermal transport in a nonequilibrium system represented by helium under a finite heat flow. We will measure the depression of the temperature of the phase transition by the flow of heat with 100 times better precision than previously. Also, we will search for any change in the nature of the transition in the presence of a finite heat flow by measuring hysteresis at the phase transition with 10 times better temperature resolution, free of gravity's influence.

Finite-Size Effects and the Role of Boundaries

Existing measurements of the static properties of helium in well-defined confined geometries are incomplete and inconsistent with each other. The Confined Helium Experiment, which flew in space in 1997, demonstrated the potential for high-resolution experiments in orbit. Measurements of dynamic properties, such as heat transport in confining media, are almost nonexistent, and the dynamic finite-size scaling theories are yet to be developed. The behavior of helium confined to one or two dimensions is known to be fundamentally different from the behavior of helium in three dimensions, yet high-precision measurements are just being started. Evidence for crossover of behaviors from 3-dimensional to 2-dimensional is rare, and the results are inconsistent with theories. The effects that solid boundaries exert on a phase transition are poorly understood — even though such effects are of fundamental importance to the problem.



Isolated drops of superfluid helium in microgravity will display fundamental motions of a large quantum system. On Earth, only small drops may be isolated from walls to observe the fundamental motions, and gravity distorts the drops.

Large-Scale Quantum Systems

Superfluid ^{4}He and ^{3}He represent large-scale systems occupying a single quantum state. On Earth, their behavior is strongly affected by the confining walls of a container. A drop levitated in space will permit new tests of quantized motions to be performed. Mixtures of these two isotopes of helium are also expected to display unique phases in drops.

Thick Helium Films

Studies of films on Earth are restricted to thicknesses of only a few hundred atomic layers because gravity causes thicker films to drain, so the film becomes nonuniform. Films display many special behaviors that are of fundamental interest. The low-gravity conditions permit thicker and more uniform films to be obtained. The transition from thin-film behavior to bulk-fluid behavior can be observed as the film thickness is increased. Issues to be addressed include the influence of the film thickness on the superfluid phase transition, the propagation of sound in films, and the crossover from 2-dimensional to 3-dimensional behaviors.

Melting–Freezing and the Growth of Crystals

Gravity has several influences on how crystals grow from a liquid. Helium's unique properties, including rapid thermal diffusion and equilibration, permit observation of the fundamental processes involved in crystal growth during the relatively short periods of low gravity available. Studies of mechanisms for transfer of atoms from liquid to solid, the nucleation of new phases, the evolution of crystal shapes, mechanisms for mass transport, and other topics may be observable in this material.

Hydrodynamics of Quantum Fluids

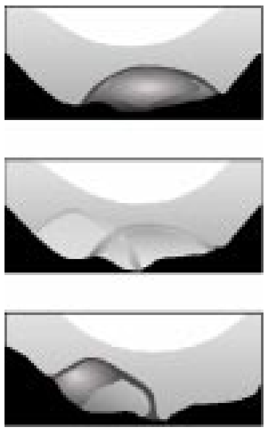
When studied on Earth, the motions of superfluid helium are intimately influenced by the container walls. Attempts to study the nucleation of vortices as the liquid is slowly rotated invariably suffer from this influence of the walls. By performing the experiment in low gravity, large samples of the liquid can be levitated away from the walls, so the truly intrinsic response of the isolated liquid can be observed. The low-gravity condition allows the liquid drop to be observed with minimal disturbance for long periods.

Pattern Formation

Applying stress to a fluid to move it far from equilibrium can cause a transition from a uniform state to one having spatial variations. Such pattern formation is of fundamental interest to scientists because it is observed not only in pure fluids, but also in chemical, biological, and other physical systems. Gravity often acts to obscure or distort the formation of such patterns, so studying these effects in orbit will provide advantages.

Low-Density Granular Materials and Fractal Structures

The study of the flow of granular materials has much practical significance, but these flows are always influenced strongly by gravity on Earth. The complex dynamical properties involved will be much better elucidated under low-gravity conditions. Low-density granular aggregates can display fractal properties, but their study on Earth is hampered by the tendency to collapse under their own weight.



A system under an applied stress will often undergo a transformation from a uniform state to one with spatial variations that may show patterns. Such nonlinear effects are of fundamental importance to physics. Gravity often obscures the onset and will influence the formation of these patterns. These three frames show a metastable solid phase of helium rapidly transforming into the stable phase (top to bottom), each frame representing 1/32 second. On Earth, the shapes and positions of the solid phases are strongly influenced by gravity, and the growth of the solid will be affected by gravity-driven convection. Both fundamental and technological aspects of these phase transformations can be studied better in microgravity.

Space Experiments: Past and Future

Past NASA Space Experiments

EXPERIMENT	DATE	ACHIEVEMENT
Lambda Point Experiment (LPE)	*1991*	*Measured static property of liquid helium near a phase transition. Proved that gravitational smearing can be removed in microgravity. Showed that very precise measurements can be performed in space. Demonstrated that the phase transition in helium is still sharp at the 10^{-9} kelvin level.*
Critical Fluid Light Scattering Experiment (ZENO)	*1993, 1996*	*Measured light scattering in xenon very near the liquid–gas critical point. Demonstrated that the liquid–gas critical point can be studied in space. Measured the relaxation rate of the density fluctuations. Observed equilibration rates for temperature and density.*
Critical Viscosity Experiment (CVX)	*1997*	*Measured the viscosity of xenon close to the gas–liquid critical point. Obtained the first viscosity measurements in the asymptotic region. Derived new, more accurate values for the critical exponent, γ.*
Confined Helium Experiment	*1997*	*Measured static property of helium confined to planar gaps between plates. Obtained the most accurate finite-size data of a confined system very close to criticality. Demonstrated improved temperature measurement precision in space.*

Past European Space Experiments

MISSION	DATE	ACHIEVEMENT
German Spacelab Mission D1	*10/85*	*Isochoric heat capacity at the critical point of SF6.*
German Spacelab Mission D2	*4/93*	*Isochoric heat capacity as in D1, and piston effect (dynamic temperature propagation) near the critical point of SF6.*
Spacelab IML-1 (ESA)	*1/92*	*Static and dynamic properties of fluids near the liquid–vapor critical point.*
EURECA	*8/92*	*Study of adsorption of SF6 close to its critical point on graphitized carbon.*
Space IML-2 (ESA)	*7/94*	*Static and dynamic properties of fluids near the liquid–vapor critical point.*
German–Russian Space Mission MIR	*2/97*	*Kinetics of phase transition around the critical point of a pure fluid.*

Planned NASA Space Experiments

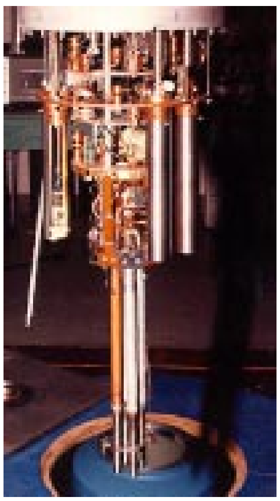
EXPERIMENT	DATE	GOAL
Critical Dynamics in Microgravity Experiment (DYNAMX)	*2003*	*Measure the effects of applying heat to liquid helium close to the transition. Derive the thermal conductivity very near the lambda transition. Determine the shift of the transition temperature as heat flow varies. Investigate change in the nature of the transition — is it hysteretic?*
Microgravity Scaling Theory Experiment (MISTE)	*2003*	*Measure several static properties at the gas–liquid critical point in ^{3}He. Test predictions of scaling laws with precise measurements.*
Superfluid Universality Experiment (SUE)	*2003*	*Measure the density of the superfluid in liquid helium at many pressures. Test that the critical parameters are universal for all pressures.*
Experiments Along Coexistence Near Tricriticality (EXACT)	*2005*	*Perform a rigorous test of the exact predictions of renormalization group theory at tricritical point (TCP). Measure the critical exponent for the superfluid density near the TCP. Determine the shape of the coexistence curve in the region of the TCP.*
Boundary Effects Near the Superfluid Transition (BEST)	*2005*	*Measure the effects of finite size on thermal transport properties near the superfluid transition. Use this knowledge to aid in the design of useful devices.*

Example Experiments

Critical Dynamics in Microgravity Experiment (DYNAMX)

MOTIVATION

Dynamic properties near second-order phase transitions have wide scientific and technological application but are relatively poorly understood.



Several stages of temperature control plus low-conductivity support provide extreme thermal stability for the measurement of heat conduction at very low applied heat currents in liquid helium near the lambda transition.

SCIENCE OBJECTIVES

Examine the dynamic properties of the superfluid transition under nonequilibrium conditions with subnanokelvin temperature resolution:

- Measure the thermal conductivity in the linear and nonlinear regions, and compare to theories
- Measure the temperature profile and its scaling behavior near the interface
- Improve determination of the transition temperature suppression by a factor of 10
- Search for the hysteresis with a factor of 100 improvement in sensitivity

MISSION DESCRIPTION

- Candidate experiment for M1 mission on LTMPF on the International Space Station
- Data acquisition: three months

MEASUREMENT STRATEGIES

- Use multiple high-resolution thermometers attached to the thermal conductivity cell sidewall
- Use heat current–biased thermal control

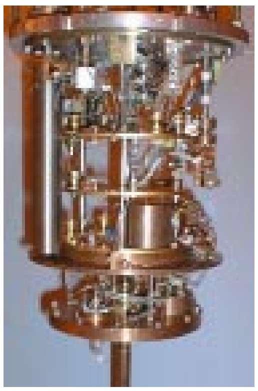
TECHNOLOGIES

- Ultracompact or thermal component–isolated high-resolution thermometer to minimize cosmic ray impacts
- Picowatt thermal control
- Composite thermal conductivity cell with ultrathin sensor probes penetrating the thin sidewall of the thermal conductivity cell

Microgravity Scaling Theory Experiment (MISTE)

MOTIVATION

Perform the most accurate test of the scaling-law predictions in a simple testbed system to improve our understanding of the range of validity of scaling theory.



For precise measurements of ^{3}He density, pressure, and temperature, sensors are included in the apparatus. The photo shows sensors and experiment cell supported on a multi-stage temperature-control system.

SCIENCE OBJECTIVES

Measure critical exponents near the ^{3}He critical point in microgravity; provide the most accurate test of scaling-law predictions:

- Perform precision measurements of the specific heat at constant volume C_V, and of the isothermal compressibility κ_T, near the liquid-gas critical point of ^{3}He in a microgravity environment
- Improve the precision of the critical exponents α, γ, δ from these measurements along the critical isochore and isotherm
- Test the scaling-law relation between these exponents and the theoretical predictions for the measured critical exponents

MISSION DESCRIPTION

- Candidate experiment for M1 mission on LTMPF on the International Space Station
- Data acquisition: three months

MEASUREMENT STRATEGY

- Develop high-resolution pressure, density, and temperature sensors to determine critical point parameters (P_c, ρ_c, and T_c) accurately and perform P, ρ, and T measurements in the critical region

TECHNOLOGIES

- Miniature $GdCl_3$ high-resolution thermometer operating near 3.3 kelvins
- Miniature cryogenic valve
- High-resolution density and pressure sensors

Superfluid Universality Experiment (SUE)

MOTIVATION

A fundamental aspect of all phase-transition theories is universality — the invariance of certain key parameters under wide variations of other non-key parameters. SUE promises to be the most stringent test of this organizing principle, which forms the basis of our understanding of a wide range of phenomena in nature, ranging from the formation of subatomic particles to the variations in the cosmic-ray background.

SCIENCE OBJECTIVES

SUE measures the superfluid density at various pressures near the lambda line of helium to test universality of the critical exponents. SUE will:

- Measure second sound velocity along isobars
- Measure heat capacity at similar pressures (ground-based)
- Measure damping coefficient
- Develop improved prediction of second-order effects

Testing universality requires operating at many well-controlled pressures. This photo shows the superconducting pressure transducer developed for SUE.

MISSION DESCRIPTION

- Candidate experiment for M1 mission on LTMPF on the International Space Station
- Data acquisition: three months

MEASUREMENT STRATEGIES

- Use custom-developed, low-level, low-dissipation signal technology
- Use custom-developed, low-dissipation, high-resolution pressure gauge
- Improve resonant frequency discrimination beyond baseline with phase-locked loop

TECHNOLOGIES

- Ultrahigh-precision, superconducting pressure sensor and regulator
- Low-dissipation thermal-wave oscillator
- Ultralow-noise thermal wave detector
- Nanokelvin thermal control

Experiments Along Coexistence Near Tricriticality (EXACT)

MOTIVATION

EXACT will perform a rigorous test at the tricritical point of liquid helium of the exact predictions of renormalization group (RG) theory. Such a test is impossible to perform in any Earth-based lab. The results will have impact on all applications of RG theories, including particle physics.

SCIENCE OBJECTIVES

Perform a rigorous test at the tricritical point of the exact predictions of theory:

- Measure the superfluid density exponent along the coexistence curve
- Measure the shape of the coexistence curve and the lambda line as a function of temperature and concentration
- Improve upon the limitations imposed by ground measurements by up to 2 orders of magnitude (factor of 100)

MISSION DESCRIPTION

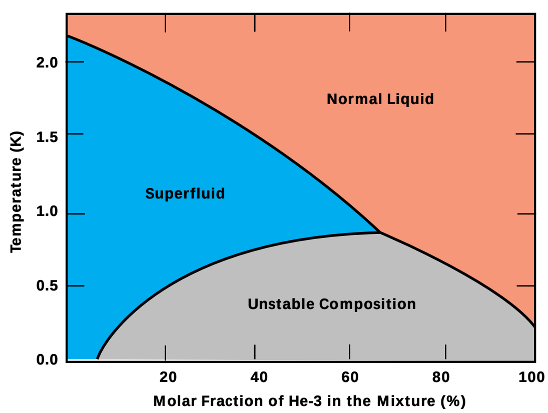
- Candidate experiment for M2 mission on LTMPF on the International Space Station
- Data acquisition: three months

MEASUREMENT STRATEGY

- Measure second sound velocity to derive the superfluid density

TECHNOLOGIES

- Cooler to reach 0.5 kelvin
- High-resolution thermometer operating near 0.5 kelvin
- ^3He–^4He mixture concentration measurement and control
- Thin-film bolometers to detect second sound temperature pulses

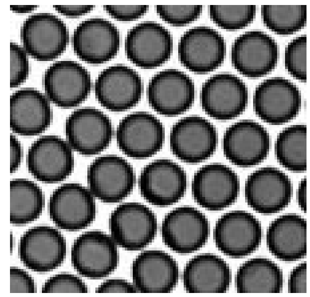


In this phase diagram for mixtures of He-3 atoms in He-4, the line (boundary) between the superfluid and normal phases terminates at the tricritical point on the phase-separation curve (the upper boundary of the unstable composition region).

Boundary Effects on the Superfluid Transition (BEST)

MOTIVATION

Provide the first test of the validity of dynamic finite-size scaling theory in nature.



An optical microscope image of a microchannel plate. One-dimensional-confinement studies in space will be performed using plates with approximately 50-micron-size cylinders.

SCIENCE OBJECTIVES

Examine quantitatively the effects of solid-boundary, finite-size confinement, and dimensionality on the critical thermal transport near the superfluid transition, and compare to dynamic finite-size scaling theory:

- Improve the measurement of thermal conductivity in a three-dimensional (3D) sample along the lambda line with 1,000 times better temperature resolution
- Measure thermal conductivity under 1D and 2D confinement of various sizes; perform analysis on dynamic finite-size scaling and compare to theoretical predictions
- Examine the crossover behavior from 3D superfluid transition to (fundamentally different) superfluid transition in 2D

MISSION DESCRIPTION

- Candidate experiment for M2 mission on LTMPF on the International Space Station
- Data acquisition: three months

MEASUREMENT STRATEGY

- Multiple thermal conductivity cells in parallel operating at the same pressure and sharing a common temperature platform

TECHNOLOGIES

- Small, high-resolution thermometers
- High-precision pressure sensor and regulation
- 1D and 2D confinement media with high uniformity and low thermal conductivity

Superfluid Hydrodynamics Experiment (SHE)

MOTIVATION

Understand superfluid hydrodynamics in the absence of perturbing surfaces. The experiment will duplicate the ideal conditions of sample isolation assumed in most theoretical calculations.

SCIENCE OBJECTIVES

Perform a detailed study of the motions of isolated drops of superfluid helium:

- Measure the dependence of the shape of a rotating superfluid drop up rotation rate
- Study the creation of vortices in rotating superfluid drops
- Measure the damping of drop oscillations
- Investigate the coalescence of superfluid drops

MISSION DESCRIPTION

- Candidate experiment for M3 mission on LTMPF on the International Space Station
- Data acquisition: three months

An experimental apparatus for levitating drops of liquid helium — a magnet at the bottom counteracts gravity forces. The apparatus includes means to manipulate the levitated drops, to introduce light into the drop region, and to record images.

MEASUREMENT STRATEGIES

- Record the drop motions with high-speed video system (1,000 frames per second)
- Use laser scattering to measure the deformation of drops

TECHNOLOGIES

- Cooler to reach 0.4 kelvin
- High-speed image recording system with minimal light requirement
- Magnetic system for controlling drop position
- Electromagnetic drive system for inducing rotation and/or oscillation of drops
- Optical access to the experimental cell at low temperature

Kinetics of the Superfluid Helium Phase Transitions (KISHT)

MOTIVATION

Understand the processes involved in a first-order phase transition, with special emphasis on the nucleation of equilibrium and nonequilibrium phases. These studies provide important information for numerous applications, such as crystal growth and preparation of materials with selected properties.

SCIENCE OBJECTIVES

Perform a detailed study of the first-order freezing–melting transition in superfluid liquid helium:

- Determine how frequently nonequilibrium phases are nucleated, and their lifetimes
- Observe the novel shapes of solid phases not influenced by gravity forces
- Measure growth rates of the solid phase from the liquid phase at many temperatures and pressures

MISSION DESCRIPTION

- Candidate experiment for M3 mission on LTMPF on the International Space Station
- Data acquisition: three months

MEASUREMENT STRATEGY

- Record the nucleation events with high-speed video system (1000 frames/second)

An apparatus for observing the formation of equilibrium and nonequilibrium solid phases of helium from the superfluid. An optical window is included for rapid image recording.

TECHNOLOGIES

- Cooler to reach 0.5 kelvin
- High-speed image recording system with minimal light requirement
- Precision pressure control system for 30 bars
- Optical access to the experimental cell at low temperature

Ground-Based Research Program

While the objective of the fundamental physics program is to perform experiments of considerable scientific significance in space, the program also supports a number of ground-based investigations. In 1998, five LTCMP experiments are under development for flight, while 25 investigations are in the LTCMP ground-based program. This strategy has several consequences for the program.

New ideas for flight experiments should be tested in a ground experiment. If the scientific merit is sufficient, then the feasibility to perform the experiment in the space facility environment must be shown. Theoretical studies of questions proposed for space experiments are performed in ground-based investigations. Calculations and modeling performed in such studies serve to better define the objectives of the flight experiment and help to demonstrate the feasibility for obtaining the desired results. Presently, five theoretical projects are supported in the LTCMP ground-based program.

The development of the techniques for the measurements and any new technologies required are often performed in ground-based tasks. The existence of the ground-based research program permits investigations covering many wide-ranging topics. Because these investigations are performed at modest cost, rather speculative proposals can be explored in the expectation of a large payoff if successful. This breadth of subject matter permits the LTCMP program to move in new directions as the scientific lore changes.

Ground-based studies also can obtain results that are important for the design of a flight experiment, or for the interpretation of the results obtained in space. While the ground-based experiments are considered the incubator of future flight experiments, many significant results, including new discoveries, have been generated through this program.

High-field-gradient superconducting magnet used by researchers to oppose gravitationally induced pressure gradients in liquid helium.

Current Ground-Based Research

INVESTIGATOR	INVESTIGATION
Prof. Guenter Ahlers	*The Superfluid Transition of ^{4}He Under Unusual Conditions*
Prof. Stephen T. Boyd	*New Phenomena in Strongly Counterflowing He-II near Tλ*
Prof. David M. Ceperley	*Prediction of Macroscopic Properties of Liquid Helium from Computer Simulation*
Dr. Talso C. Chui	*The Lambda Transition Under Superfluid Flow Conditions*
Prof. Siu-Tat Chui	*Droplets of ^{3}He–^{4}He Mixtures*
Prof. Russell J. Donnelly	*Nucleation of Quantized Vortices from Rotating Superfluid Drops*
Prof. Charles Elbaum	*Kinetic and Thermodynamic Studies of Melting–Freezing of Helium in Microgravity*
Prof. Richard A. Ferrell	*Critical Dynamics of Ambient Temperature and Low-Temperature Phase Transitions*
Dr. Ulf E. Israelsson	*Dynamic Measurements Along the Lambda Line of Helium in a Low-Gravity Simulator on the Ground*
Dr. Donald T. Jacobs	*Turbidity and Universality Around a Liquid–Liquid Critical Point*
Dr. Melora E. Larson	*Static Properties of ^{4}He in the Presence of a Heat Current in a Low-Gravity Simulator*
Dr. Melora E.. Larson	*Second Sound Measurements Near the Tricritical Point in 3He–4He Mixtures*
Prof. David M. Lee	*Studies of Atomic Free Radicals Stored in a Cryogenic Environment*
Prof. John A. Lipa	*High-Resolution Study of the Critical Region of Oxygen Using Magnetic Levitation*
Prof. John A. Lipa	*A Renewal Proposal to Study the Effect of Confinement on Transport Properties by Making Use of Helium Along the Lambda Line*
Prof. Efstratios Manousakis	*Theoretical Studies of Liquid ^{4}He Near the Superfluid Transition*
Prof. Horst Meyer	*Density Equilibrium in Fluids Near the Liquid–Vapor Critical Point*
Prof. Richard E. Packard	*Superfluid Gyroscopes for Space*
Prof. Jeevak M. Parpai	*The Effect of Thermal History, Temperature Gradients, and Gravity on Capillary Condensation of Phase-Separated Liquid ^{3}He–^{4}He Mixtures in Aerogel*
Prof. Alexander Z. Patashinski	*Nonlinear Relaxation and Fluctuations in a Nonequilibrium, Near-Critical Liquid with a Temperature Gradient*

... continued

INVESTIGATOR	**INVESTIGATION**
Dr. David Pearson	*Superfluid Density of Confined ^4He Near $T\lambda$*
Dr. Pat R. Roach	*A Microgravity Helium Dilution Cooler*
Prof. Joseph Rudnick	*Finite Size Effects Near the Liquid–Gas Critical Point of ^3He*
Prof. George M. Seidel	*Dynamics and Morphology of Superfluid Helium Drops in a Microgravity Environment*
Dr. Donald M. Strayer	*Precise Measurements of the Density and Critical Phenomena of Helium Near Phase Transitions*